Environmental Stress and Human Migration in a Low-lying Developing Nation: A Comparison of Co-evolving Natural and Human Landscapes in the Physically and Culturally Diverse Context of Bangladesh

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LONG-TERM GOALS

The relationship between environmental conditions and human migration is multidimensional and complex, and few studies have addressed exactly how this two-way relationship operates and under what conditions environmental concerns affect migration decisions. We observe that the complexity of issues facing low-lying regions such as Bangladesh demand a significant advance in knowledgebase on migration and human-environment interactions. From this view we have identified the overarching goals of our project to be: (1) identify social and environmental factors most important in maintaining stability, from households to communities, or for motivating decisions to migrate; (2) determine how these factors differ within and across diverse social and physical landscapes; and (3) assess how these variables are likely to interact under a variety of scenarios for social and environmental change.

OBJECTIVES

Our research starts from the observation that both the people and the landscape of Bangladesh have a long history of resilience. We focus our study in southwest Bangladesh because this region has (a) a diverse physical environment, (b) variation in the ways that communities provide for themselves and interact with one another, and (c) is vulnerable to a broad range of natural and anthropogenic environmental stresses. Within this varied human and physical landscape, we seek to identify patterns of resilience and adaptation to environmental challenges and to understand the role of migration, both as a strategy to enhance resilience and as a response to failures of resilience.

1. **Identify the types and characteristics of adaptive community models that comprise the socioeconomic landscape of southwest Bangladesh.** How do groups self-organize to be successful in the face of changing environment, and social and economic pressures? What are the strategies and sources of livelihood? How do these vary with socioeconomic differences?

2. **Identify the factors (physical, engineered, political, economic, social) that are most important in defining adaptive community models, including their successes, failures, and resilience.** Which factors exhibit positive or negative influences on the various community strategies? Which factors are trending toward increasing or declining importance, and over what spatial and temporal scales are they felt? Are factors endogenous or exogenous, and under whose control?

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3. **Quantify dynamics of the natural and human-modified physical landscapes relative to sea-level change.** What is the mass balance of sedimentation relative to rising sea level and subsidence? What are principal sediment sources and transport pathways sustaining vertical landscape aggradation? How has poldering of the inhabited islands impacted landscape dynamics?

4. **Assess the source and dynamics of water supplies in the region.** Where and why are there locally fresh groundwaters within a regionally saline aquifer? What role do anthropogenic modifications of the floodplain play in recharge? How are tidal channels interconnected with the groundwater system?

5. **Determine how these physical and human systems are coupled and co-evolving.** How are communities adapted to the dispersed and variable sources of potable water? How does the relationship between people and their environment vary with different livelihood strategies? How have community resilience and household vulnerability changed in response to engineered structures, shifting land use patterns, natural hazards, and long-term environmental change?

APPROACH

Study Area – We chose to set our research in the context of the poldered (embanked) landscapes of southwest Bangladesh (Fig. 1), where environmental stresses from groundwater salinity, waterlogging, storm surges, and land-use change are among the most severe in the nation. Social factors such as poverty, politics, cultural diversity, and shifting livelihoods associated with the shrimping industry are also relevant, interacting strongly with these environmental factors (Fig. 3). Within this region, we have focused our Year 1 efforts on a particular poldered island that was devastated when its embankments were breached in five locations during a May 2009 cyclone (Fig. 4). Most of these breaches were not repaired until spring 2011, with one major breach still open today. During much of the intervening two years, the landscape remained intertidal, displacing 1000s of families and precluding agriculture or shrimp production, two of the principal livelihoods in the area.

Research Framework – In Year 1 we designed an overarching project framework that we refer to as an Integrated Social, Environmental, and Engineering (ISEE) model (Fig. 2). Our ISEE model integrates social, environmental, and engineering data in the study of human-environment coupling. The research can take place within any number of contexts (shown in purple), each of which defines a unique perspective on the coupled human-environmental system. The study context acts as a prism through which we identify and measure a number of factors (shown in blue) that describe aspects of the human-environmental interactions relevant to the study context. Interactions among these factors are analyzed to identify patterns of action by which the populace makes its livelihood. We analyze these patterns to identify dynamic equilibria (shown in green) through which communities are able to provide for themselves under ordinary conditions, and which are also sufficiently flexible to adapt to changing stresses in the physical and human environments. A major underlying hypothesis of this conceptual framework is that a community whose livelihoods comprise multiple dynamic equilibria will be more resilient, because it can adapt to the collapse of any single equilibrium by shifting activity to another.

Year 2 efforts have focused on the analysis of extensive field data collected in Year 1 within the ISEE model framework. Data have been gathered through both the mining of available resources and the collection of repeated, seasonal field observations. Current activities at the transition from Yr-2 to Yr-3 center on the goals of testing and integration of ideas from the various research efforts, and the initial scaling of ideas and observations via remote sensing. In terms of testing ideas, the field-based teams continue to analyze data with the goal of evaluating emergent field hypotheses against carefully

documented data-based observations. This process has involved activities from the referencing of GPS, land, and water surface elevations to a common datum, to the coupling of groundwater transport and geochemistry, to the coding of social-science field interviews for grounded-theory qualitative analysis. The integration of these team efforts are proceeding through the ongoing construction of a GIS-based data framework and the initial design and implementation of agent-based models. The up-scaling of outputs are being considered through remote sensing of EVI patterns across the region that share common phenologies (see Study Area). We are also in the process of developing an analytical framework that will allow us to evaluate data generated through the conceptual ISEE model into increasingly concrete findings and refined, testable hypotheses (Fig. 3). The analytical framework provides a normative context for comparing the results among diverse social and physical datasets, the outcomes of which will then be evaluated through computational ABM models that explore a variety of plausible scenarios.

Toward scaling our observations to the broader coastal region, our efforts have been focused on developing the analytical tools and image archives necessary for the multi-temporal, multi-scale analysis of remote sensing images. We have developed a combined EOF analysis and temporal mixture model (described in detail in Small 2012) to quantify spatiotemporal processes captured by the MODIS vegetation image time series. We have also produced a seasonally consistent anniversary pair of Landsat mosaics of the delta to use as an exploratory tool for identifying decadal changes. The mosaic, along with a series of full resolution regional change pairs, is available online at: http://www.ldeo.columbia.edu/~small/dBang/

Field Work – Our Year 2 field efforts include four major field campaigns in October 2012 and February, May and September 2013 involving eight PIs (Goodbred, Ackerly, Gilligan, Ayers, Donato, Steckler, Seeber, Small), two post-docs (Wilson, Carrico), and eight graduate students, and numerous local partners from Khulna University (K. Roy, D. Datta), Dhaka University (S. Imtiaz), and Jahangirnagar University (M. Anam). The October 2012 trip was a follow-up field effort to retrieve late wet-season data for the physical research teams investigating water resources, hydrology, and landscape dynamics. The February 2013 trip was a multi-institutional field effort involving PIs and students from Vanderbilt and Columbia Universities. The installation of GPS stations at the Polder 32 field site and at three coastal tide gauges was headed by PI Steckler. Joint field activities included the ground-truthing of remote sensing observations made by PI Small and Vanderbilt PDF Wilson and PhD student Benneyworth. The water resource teams also collected a second dry season set of samples. In May 2013, the QCA and Experimental teams (Carella, Nay) returned for a field effort to follow up from the May 2012 dataset (QCA) and to establish a baseline framework for the planned Experimental research efforts (Ackerly, Mo). In September 2013 the BEMS migration team launched its pilot study of 200 household surveys in the field area.

WORK COMPLETED

The social-science group, headed by Brooke Ackerly, gathered community-level qualitative data during the May 2012 field campaign and followed with a subsequent field effort in May 2013. This team used a multi-method approach that included Participatory Rapid Appraisal (PRA), Key Informant Interviews (KII), and Focus Group Discussions (FGD), aimed at gathering data on livelihoods, mobility, common pool resources, and evidence of community stability and instability. In Year 2 these data have been transcribed, translated and are currently being coded to allow analysis and identification of key physical, engineered, social, economic, and political factors that contribute to community stability and instability.

The Bangladesh Environment and Migration Survey (BEMS) effort headed by Katharine Donato was developed in Year 2 and is currently being implemented as a 200-household pilot survey in September 2013. The BEMS consists of two instruments: a household ethnosurvey and community survey. The household ethnosurvey is being administered to self-identified household heads and spouses in randomly selected households. It collects information about the following: demographics, economic activity, income, assets, livelihoods, internal and international migration trips, access to services (e.g., health care, education), access to food and water, nutrition, health, social networks, perceptions and responses to environmental change. The community survey collects information using key informant interviews about infrastructure, services, and economic activity at the mouza level including: markets, health care facilities, schools, water sources, employment, NGOs, and government aid.

The physical-science group, headed by Steve Goodbred, led a team from Vanderbilt, Dhaka, and Khulna universities to the field in May 2012, followed by a reconnaissance data collection in October 2012, February 2013, and May 2013, each led by post-doctoral fellow, Carol Wilson. The physical-science team used a fast-static GPS and theodolite campaign (Steckler) to measure absolute elevations of the landscape and engineered-structures within the study area (Fig. 7). Sedimentation rates have been measured by shallow coring and an array of surface sediment traps in conjunction with data loggers for water elevation, conductivity, temperature (Goodbred). Tidal-groundwater interactions were further investigated through a one-dimensional groundwater flow model interacting with two tidal river channels (Hornberger; Fig. 8). Surface and groundwater resources have been evaluated by chemical analyses (ICP-OES, IC, TOC) to identify mixing trends between tidal channels, drinking water ponds, brine shrimp ponds, and tubewells (Ayers; Fig. 9).

In Year 2 the geophysics team, headed by Mike Steckler, added GPS receivers at the locations of two tide gauges to distinguish absolute sea level rise from subsidence (Fig. 10). Sites were also chosen near groundwater monitoring wells to better constrain the absolute motions of the sea surface, land surface and groundwater table, particularly near the coast, that are most susceptibility to large storms and storm surges. Subsequent years will focus on analysis of these new GPS data, our existing network of 25 continuous GPS and the extensive BWDB hydrographic network to investigate the landscape changes, and groundtruthing the remote sensing data near the coast. The geophysical surveys are also complemented by structural geology investigations headed by Leonardo Seeber aimed at defining the regional seismic threat and the role that tectonic deformation plays in land-surface elevation changes in the coastal zone (ie., subsidence and layer parallel shortening; Fig. 11).

The integrative team, headed by Jonathan Gilligan, is developing an agent-based modeling (ABM) component of the project. ABM is fundamentally a bottom-up approach that aims to understand and explain complex behaviors at the system level (macro-behavior) as emergent phenomena that arise from relatively simple behaviors at the individual level. Determining how simple the micro-level should be involves iteratively coding many models and conducting sensitivity tests. A top-down system-dynamics approach requires less labor and computational resources, but neglects heterogeneity of decisions and behaviors at the micro-level and thus risks merely describing rather than explaining emergent phenomena.

Also coupled with the integrated project framework are region-wide remote-sensing analysis of tasked and archival satellite images by Chris Small (Fig 6). These are being analyzed using multi-scale, multi-temporal spectra-mixture modeling, based on a combined EOF analysis and temporal mixture model applied to MODIS-derived vegetation indices. In addition to the spatiotemporal analysis of the Landsat imagery described above, we plan to apply it to a time series of 25 ALOS PALSAR synthetic aperture radar of the southern GB delta collected between 2006 and 2011. The

SAR imagery has 6 to 12 m spatial resolution and is complementary to the Landsat imagery in its ability to distinguish standing water from wet soil, dry soil and agriculture. In addition to parallel spatiotemporal analyses of the Landsat and PALSAR data, we will attempt combined analysis – of both spatiotemporal structure and physical responses the optical and microwave spectrum to different land cover types common to the GB delta. We are currently processing the Landsat and PALSAR time series and expect to have results by the end of the calendar year.

RESULTS

Our research is progressing well and we are increasingly confident that our conceptual framework is the proper one to contribute to identifying the most important vulnerabilities and the most important opportunities to build and enhance resilience in the face of environmental stress from natural and human causes. Awareness of the connections between a changing physical environment and changes in social, political, and economic conditions has the potential to inform decision-making, both at the policy-making level of choosing which measures to pursue and in effectively implementing those measures. As our current research continues to evolve rapidly with the processing and analysis of new data and integration of results, we present here two excerpted discussions from our recent scholarship.

The following two passages are excerpted from recent a conference proceeding and submitted manuscript. Their perspective is grounded in the ISEE framework and based on our emphasis of poldering (i.e., embanked landscapes) as the defining context of study in the region of southwest Bangladesh. We present these excerpts as examples of the interdisciplinary perspectives and outputs that our research is generating concerning coupled human-landscape interactions.

Excerpted from conference paper, **"Building resilience to environmental stress in coastal Bangladesh: An integrated social, environmental, and engineering perspective"** developed by Gilligan, Ackerly, and Goodbred and presented at Bangladesh Development Institute Conference, Berkeley, CA, Feb. 2013 ———

To date the core of our theoretical framework and methods is the hypothesis that communities are resilient because of multiple dynamic equilibria. A dynamical equilibrium is a metaphor adopted from physics, where a system that is unstable at rest becomes stable in motion. An analysis of vulnerability to natural hazards in Bangladesh has gone astray when it considers only a static snapshot rather than the dynamics of people's livelihoods.

The Flood Action Plan proposed in 1989, is such a case. The flood action plan observed that the severe monsoon flooding in 1987 and again in 1988 were devastating and proposed a massive engineering project to control and contain monsoon waters to prevent future flooding.(Boyce, 1990) But by focusing only on specific moments of time in which exceptional floods were harming people, the planners failed to see how their project would disrupt the normal cycle of flooding.(N. Islam, 1990; B. K. Paul, 1995; Rasid, 1993; Rasid & Haider, 2003; Rasid & Mallik, 1993) The people of Bangladesh have adapted to annual monsoon flooding, where the normal range of floods acts as a resource that maintains the fertility of farmland and provides opportunities to harvest and raise fish—an important source of protein. The seasonal rhythms of livelihood, accommodating and exploiting the annual monsoon cycle, is an example of a dynamic equilibrium, and the public's rejection of the Flood Action Plan illustrates the importance of understanding dynamics when designing and analyzing policy for natural hazards.

One question our project is investigating is whether the Coastal Embankment Project's construction of massive polders during the 1950s and 60s suffered from a similar failure to appreciate dynamics. The polders produce a lot of good by creating dry land for farming and habitation on what were previously intertidal lands, but they also create new hazards and experts on the tidal river systems have suggested that the benefits of polders could have been realized with less collateral damages and dangers if they had used Tidal River Management (TRM) instead.(M. R. Islam, 2006; Kibria, 2011) TRM is adapted from a traditional practice in which smaller embankments were constructed each year during the dry season to keep salty water off the land, and torn down during the wet season to allow sweet rain-fed monsoon water to wash over the land, depositing fresh sediment and washing away contaminants.

TRM is a controversial topic and this controversy erupted into political violence this summer in Jessore.(The Daily Sun, 2012) This violence illustrates that it is necessary to understand not only the science, but also the social, political, and economic context and consequences of engineering projects.

While dynamics can enhance the stability of a pattern of livelihood, exceptional circumstances can disrupt even a dynamic equilibrium, just as the 1987 and 88 floods disrupted the adaptation to the normal monsoon cycle. We hypothesize that communities whose livelihood involves multiple dynamic equilibria will be more resilient because when one dynamic equilibrium is disrupted, others can provide support. These multiple dynamic equilibria may involve not just activities within a single community, but interactions between multiple communities. In the community we studied, people engaged in rice farming locally but also engaged in seasonal migrant work on rice farms in a distant part of the country. When Cyclone Aila rendered local farmland unusable for several years, the established pattern of migrant farmwork and the network that had developed to facilitate it served to provide livelihoods for people who might otherwise have had few options.

To study multiple dynamic equilibria, we look for patterns in the relationships between the factors relevant to our context of study. An active question in our research is to determine at which scales multiple dynamic equilibria are a sign of resilience and health and at which scales they are signs of stress and desperation. It appears to be healthy for a community to have a diverse collection of activities by which its members make their livelihoods. This diversity protects the community from events that render one livelihood activity dysfunctional. However, we have anecdotal observations, as well as theoretical reasons to believe that at the individual level, diversity of livelihood activities may be a sign of desperation rather than resilience. Having to switch from one activity to another to another over the course of the year to make a living can prevent people from doing any one activity intensively enough to develop expertise, and may take them away from the activities they do best. In a truly resilient state, people who have exceptional ability as a farmer would farm all the time, whereas if they become desperate they may have to engage in many activities, such as fishing and aquaculture, to which they are not well suited. As the saying goes, they risk becoming "a jack of all trades and master of none." Assessing these competing effects of diversification and specialization remains a priority as our project moves forward.

Excerpted from manuscript ***In the Balance: Natural vs. Embanked Landscapes in the Ganges-Brahmaputra Tidal Delta Plain*** by Auerbach, Goodbred, Mondal, Wilson, Ahmed, Roy, Steckler, Gilligan, and Ackerly. Submitted to *Nature:Climate Change;* Sept. 2013 ———

Here we report findings from the low-lying, embanked delta-plain of southwest Bangladesh, which exhibit both greater risk and greater resilience to storms and relative sea-level change than previously reported. In its natural state, sediment aggradation on the G-B delta is sustained by the transport of ~1

billion tons of sediment annually from the Himalaya to Bay of Bengal, primarily during the five months of summer monsoon. If dispersed equally across the 150 million km^2 of terrestrial and marine portions of the delta, this load can account for ~0.5 cm/yr of sediment aggradation, roughly equivalent to relative sea level (RSL) rise measured at several coastal tide gauges. However, rates of sedimentation are not evenly distributed; they vary widely, as do rates of RSL change due to differences in subsidence and compaction. Overall, these values and patterns are poorly constrained for the G-B and many of the world's delta systems. Nevertheless, such variations in sedimentation and subsidence will define the local responses of deltas to increased rates of sea-level rise.

Over the last several hundred years the Ganges river has shifted progressively east, isolating the central and western deltaplain from its principal source of sediment. The jewel of this landscape is the Sundarbans mangrove forest, a 10,000 km^2 UNESCO World Heritage site. Here the regular input of sediment by tidal inundation has maintained elevation of this 'abandoned' delta-plain for millennia, with an average of only 4 km^2/yr land loss during the last two centuries (balanced by a net gain of 12 km^2/yr in the eastern delta). Overall the physical environment of the Sundarbans remains robust with no major land loss or conversion to open water. Bordering the pristine Sundarbans to the north is a starkly contrasting, human-modified environment that comprises more than 50 large islands, formerly forested and intertidal. The islands were cleared over time and ultimately embanked in the 1960s and 1970s in an effort to relieve famine by increasing arable land for paddy cultivation. Referred to by their Dutch name, *polder*, these islands are normally protected from tidal and storm-surge inundation by earthen embankments constructed around the margins. However, in addition to stemming floodwater, the embankments also preclude the deposition of sediment and organic matter that normally sustains the elevation and fertility of the landscape.

In May 2012 we conducted a fast-static GPS and theodolite survey of land-surface elevations on Polder 32, a 60-km^2 island in the Dacope upazilla of Bangladesh's Khulna division, including measurements from the adjacent Sundarbans forest. Results show that mean elevation of the Sundarbans lies at 2.65±0.10 m relative to the EGM96 datum; in contrast, mean surface elevation of the poldered landscape is 1.50±0.50 m, which is >1 m lower than that of the Sundarbans (Fig. 7). This disparity in elevation represents an average loss of ~2 cm/yr of RSL in the five decades since polder construction. This rate of effective sea-level rise is more than twice the upper end of the IPCC projections, making these poldered landscapes a useful, albeit troubling, analog for studying the impacts of increased sea-level rise in coming decades.

Storms are one of the greatest threats facing people in low-lying coastal regions, and on May 25, 2009, Cyclone Aila struck West Bengal, India, and southwestern Bangladesh as a Category 1 storm. Cyclone Aila caused five major breaches of the embankments protecting the western margin of Polder 32. Within months of the storm several of the breaches had been closed by locally repairing the embankment, but poor build quality led to nearly complete failure again in early 2010. Although the history of embankment repair since the storm has been complicated, 18 to 24 months passed before most of the breaches were soundly repaired, with the largest remaining unrepaired as of early 2013.

In the roughly 2-year period prior to embankment repair, the polder's low elevation relative to normal tide levels ensured that it was submerged on every tide to a mean depth of 100 cm and for an average of 9.8 hours per day. By contrast the pristine Sundarbans, which are >1 m higher in elevation than the polder, are inundated only during spring high tides (36.6% of all tides) and only to a mean depth of 20 cm for 1.7 hours per day. It is here, at the boundary of two juxtaposed landscapes, that the profound impacts of subsidence and sediment starvation become acutely apparent. In this case the historical loss of elevation relative to local water level has severely exacerbated the effects of tidal inundation by increasing the tidal prism (volume of water moving on and off the landscape),

accounting for the exchange of ~62 $\times 10^6$ m^3 of water through the breaches during each tidal cycle. By contrast the tidal prism would have been 4-fold smaller if Polder 32 were at the equilibrium elevation of the adjacent Sundarbans.

Coupled with the increased frequency and depth of tidal inundation relative to the Sundarbans, rapid sediment deposition on the polder led to a mean accretion of 40 cm in the two years following the storm, with many sites as high as 60-70 cm. This equates to a mean annual accretion rate of ~20 cm/yr, which is more than an order of magnitude faster than the background sedimentation rates in the Sundarbans. The exceedingly high rates of sedimentation following the embankment breaches exemplify the efficiency with which the tides and G-B fluvial system can disperse sediment to areas of accommodation, particularly where space has been generated through anthropogenically enhanced RSL rise. In this case it was the >1-m loss in relative elevation that set the potential for rapid accretion following Cyclone Aila. Furthermore, such low land-surface elevations are found not only on Polder 32 but most embanked islands in southwest Bangladesh, giving considerable concern for more widespread impact of breaches and flooding..

Beyond Polder 32, we have observed that most embanked islands in southwest Bangladesh have experienced a similar elevation loss and now lie well below mean high water, similar to circumstances in Dutch and Belgian polders This highlights the vulnerability of these human-modified regions to increased sea levels as a result of inhibited sediment delivery. In total Bangladesh incorporates 123 polders that are maintained by over 5000 km of embankments**.** If inhibited sediment delivery has resulted in the widespread loss of elevation across the poldered regions, then the immediate threat to the G-B tidal delta plain appears to be one of human-manipulation of the local environment rather than global sea-level rise. The silver lining for Bangladesh and the G-B delta remains the one billion tons of sediment annually delivered and, where so allowed, effectively dispersed onto the landscape. Ultimately the complex picture that emerges contrasts the risk posed by relative elevation loss in many embanked areas with the natural system's resilience through rapid potential sediment aggradation, raising both concern and hope for this densely populated region.

IMPACT/APPLICATIONS

Our research will ultimately lead us to distinguish those attributes of society and environment that favor stability and resiliency among interconnected communities compared with those that undermine local capacity to thrive within a dynamic physical environment.

RELATED PROJECTS

Several PIs from the physical-science team of the ONR MURI project are also collaborating on a National Science Foundation study investigating coupled fluvial-tectonic-basin interactions in the Bengal Basin and Ganges-Brahmaputra River delta. This project is led by ONR co-PI Michael Steckler at Columbia University, and also includes other ONR co-PIs Steven Goodbred (Vanderbilt) and Leonardo Seeber (Columbia). The project is funded through NSF International Program's Partnerships for International Research and Education (PIRE). The project title is "Life on a tectonically active delta: Convergence of earth science and geohazard research in Bangladesh with education and capacity building". More information can be found at the project homepage http://www.banglapire.org/. To date the most important links between the studies are expanded capacity for monitoring and understanding tectonic deformation of the basin and its impacts on subsidence, sedimentation, and river behavior.

FIGURES and TABLES

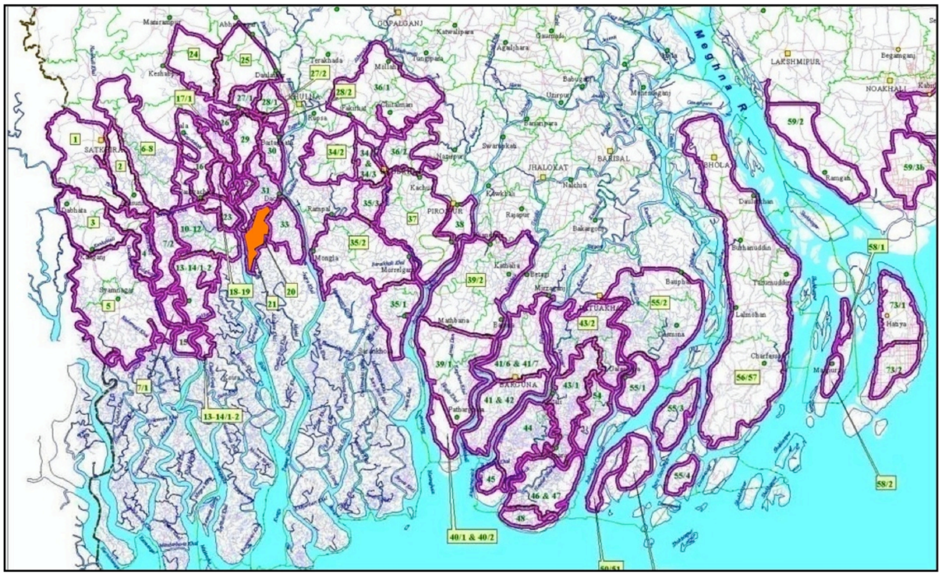

Figure 1. Map of the widespread polder systems in coastal Bangladesh. Polders are lands that have been embanked for protection from flooding. Most embankments were constructed in the 1960s and 1970s as part of the Coastal Embankment Project, which was aimed at increasing arable land for paddy cultivation and famine relief. The Year 1 project site is shown in orange.

Figure 2. Field photos from the study area. (upper left) Photo of an embankment at high tide, highlighting relative elevation difference (~1.5 m) between high water and the poldered landscape; (upper right) The 'hanging village', a fishing community living along the embankments; (lower left) PI Brooke Ackerly interacting with families in the 'hanging village'; (lower right) Group of women following an interview for seasonal livelihood mapping via participatory rapid appraisal.

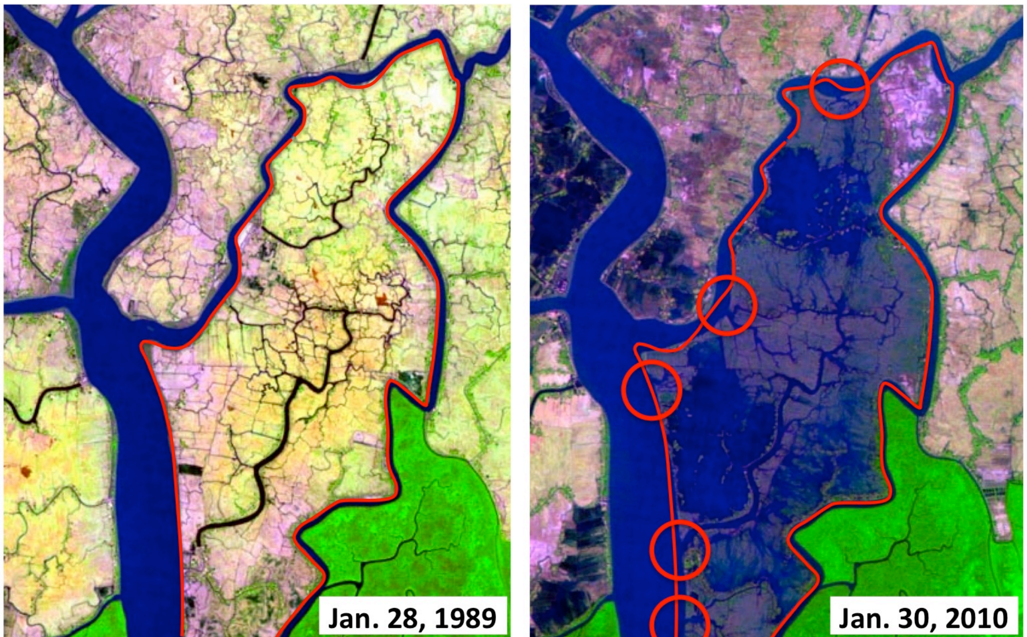

Figure 3. Dry-season Landsat images of the focus study area in 1989 and 2010. 2010 image taken 8 months after Cyclone Aila, showing most of the landscape wet or inundated by tidal waters (image taken near low tide). Red lines show 1989 bank positions, with red circles denoting the location of five major breaches caused by Cyclone Aila, all occurring at locations of historical channel-bank migration.

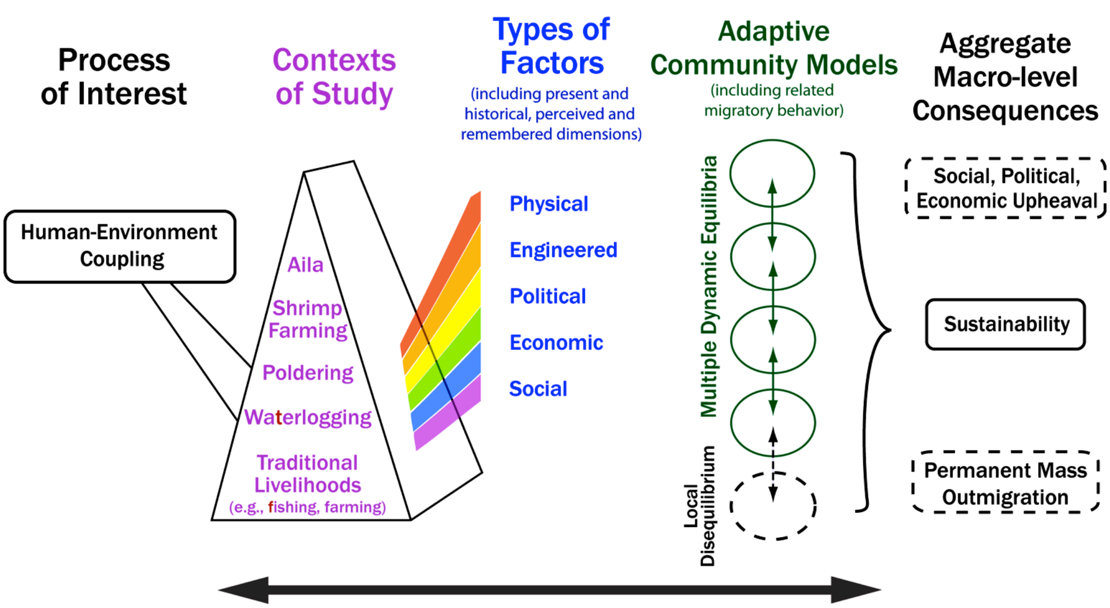

Figure 4. Integrated Social, Environmental, and Engineering (ISEE) model. This model was developed by our team to serve as the primary conceptual framework for all research activities. Model structure explained in text (section Approach: Framework)

Our current understanding of project results is that climate change is not *the* story, but one part of a more complex history that comprises poldering, famine, the war of liberation and subsequent struggles as an independent nation emerged, on top of which environmental changes, some climatic and others not, relative sea level change, sediment dynamics, chemistry of the tidal channels, and storms hitting the coast. Current environmental stresses include:

- groundwater salinity (possibly changing, but we don't know).
- depleted fisheries
- amplification of storm surges as the tidal channels and platforms evolve

In the future, global climate change will add possible changes to

- sea level
- monsoon timing and intensity

To understand the impacts of these changes, we seek to define more clearly what is meant by the terms *vulnerability, capacity, capability, resilience,* and *sustainability.*

$$RISK = THREAT \times PROBABILITY \times CONSEQUENCES$$

$$CONSEQUENCES = f(loss\ of\ life, infrastructure, livestock, crops, livelihoods, cohesion, water, soil, landscape)$$

$$VULNERABILITY = \frac{RISK}{CAPACITY} \quad \text{and} \quad CAPABILITY = \frac{CAPACITY}{RISK}$$

$$\frac{VULNERABILITY}{CAPABILITY} = 1$$

$$CAPACITY = f(wealth, cohesion, workpower, livelihoods, connectivity, aid, infrastructure)$$

$$RESILIENCE = CAPABILITY \times ACTION \quad \text{or} \quad \frac{ACTION}{VULNERABILITY}$$

$$PERTURBATION = DURATION \times RATE \times MAGNITUDE \times FREQUENCY$$

$$SUSTAINABILITY_i = \left(\sum_i \frac{PERTURBATION}{RESILIENCE}\right)^{-1}$$

Figure 5. Draft of the concepts and definitions that will provide the basis for an analytical framework in which to evaluate data and observations generated during physical and social field research. Field data were collected in the ISEE model framework, where results related to the "blue factors"(see Fig. 1) are used to evaluate vulnerability and capability in the analytical framework below. The "green circles" (adaptive community models) in the ISEE framework (Fig. 1) correspond with resilience, where capability and vulnerability that are controlled by the "blue factors" are coupled with community and individual action that together define resilience.

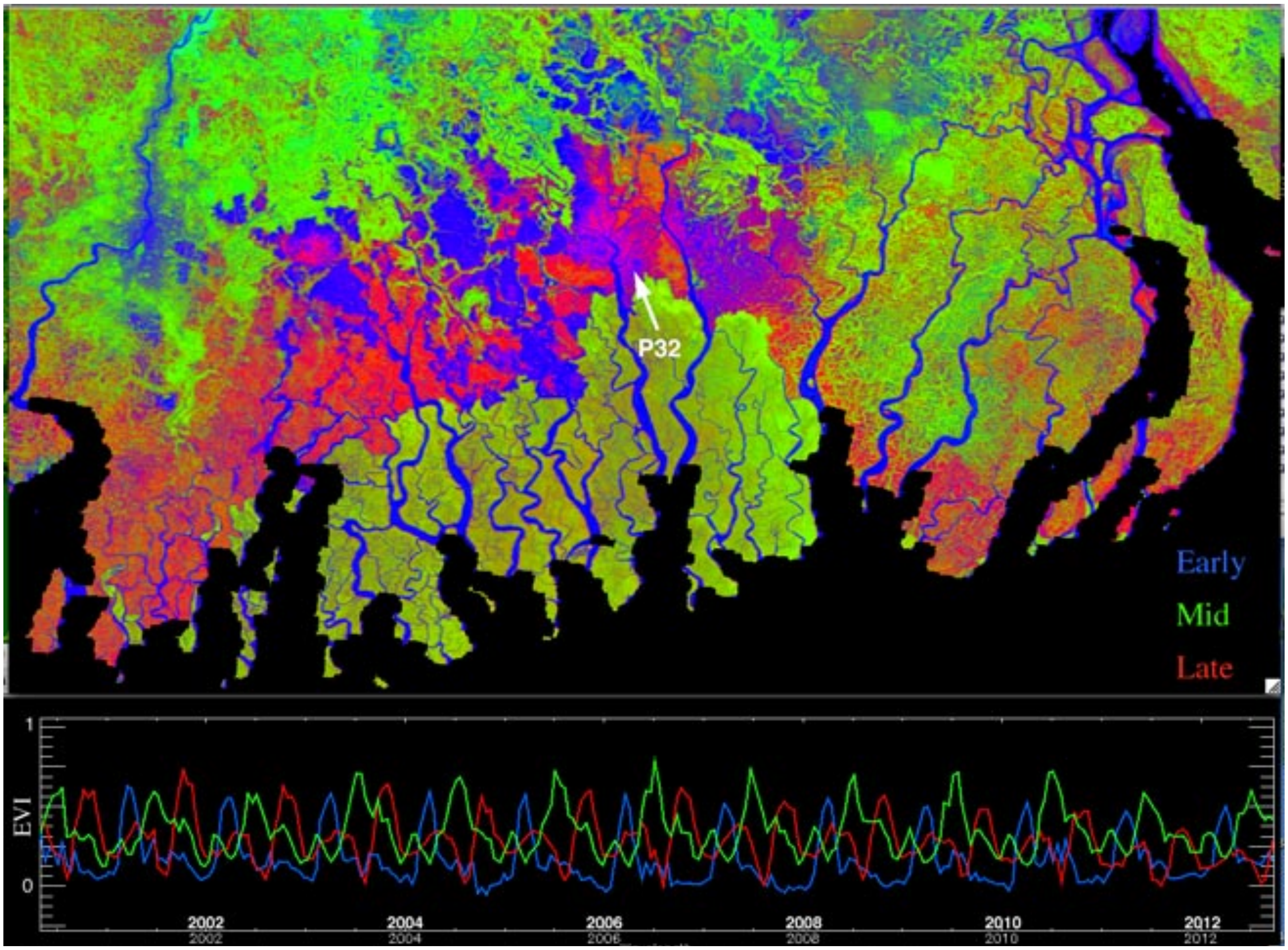

Figure 6. Decadal phenology map derived from 12 years of MODIS Enhanced Vegetation Index (EVI) imagery. Phenology map is derived from a linear temporal mixture model of similarity to phenological endmembers (bottom). Early, Late, and Mid-year peak vegetation abundance endmembers correspond to the most statistically distinct annual phenologies. The evergreen Sundarbans are represented as mixtures of Mid and Late greening period endmembers because of changing solar illumination. River channels and shrimp ponds appear blue (with greater misfit) because the model has no non-vegetated endmember.

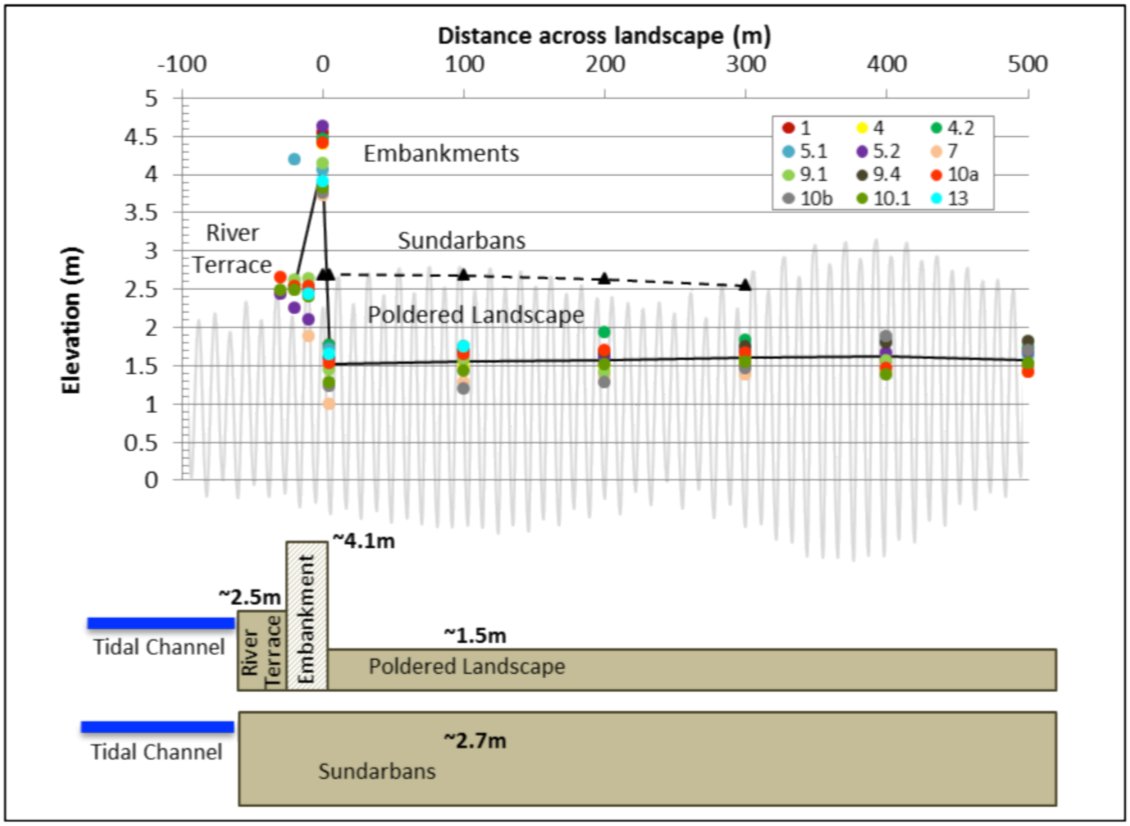

Figure 7. Results of the GPS elevation survey along with a conceptual model of the poldered and natural landscapes. On the plot, colored circles correspond to Polder 32 survey transects, the black triangles correspond to the Sundarbans transect, and spring and neap tidal cycles are shown via gray line. The Sundarbans platform, which is positioned at +2.65 m relative to the EGM96 datum, is flooded only during spring high tides. River terraces outboard of embankments on Polder 32 are positioned at approximately the same position as the Sundarbans, which indicates that these frequently flooded regions are capable of maintaining equilibrium elevation. Embankment heights across the polder range in elevation from +3.7 to +4.6 m. Cement embankment structures are generally positioned at higher elevations than earthen embankments, which explains the variability in embankment elevations. The poldered landscape is positioned at +1.5 m and, in the absence of embankment protection, is flooded at every high tide. The local practice of borrowing sediment closest to the embankments during repairs has caused consistently lowered polder elevations inboard of the embankments.

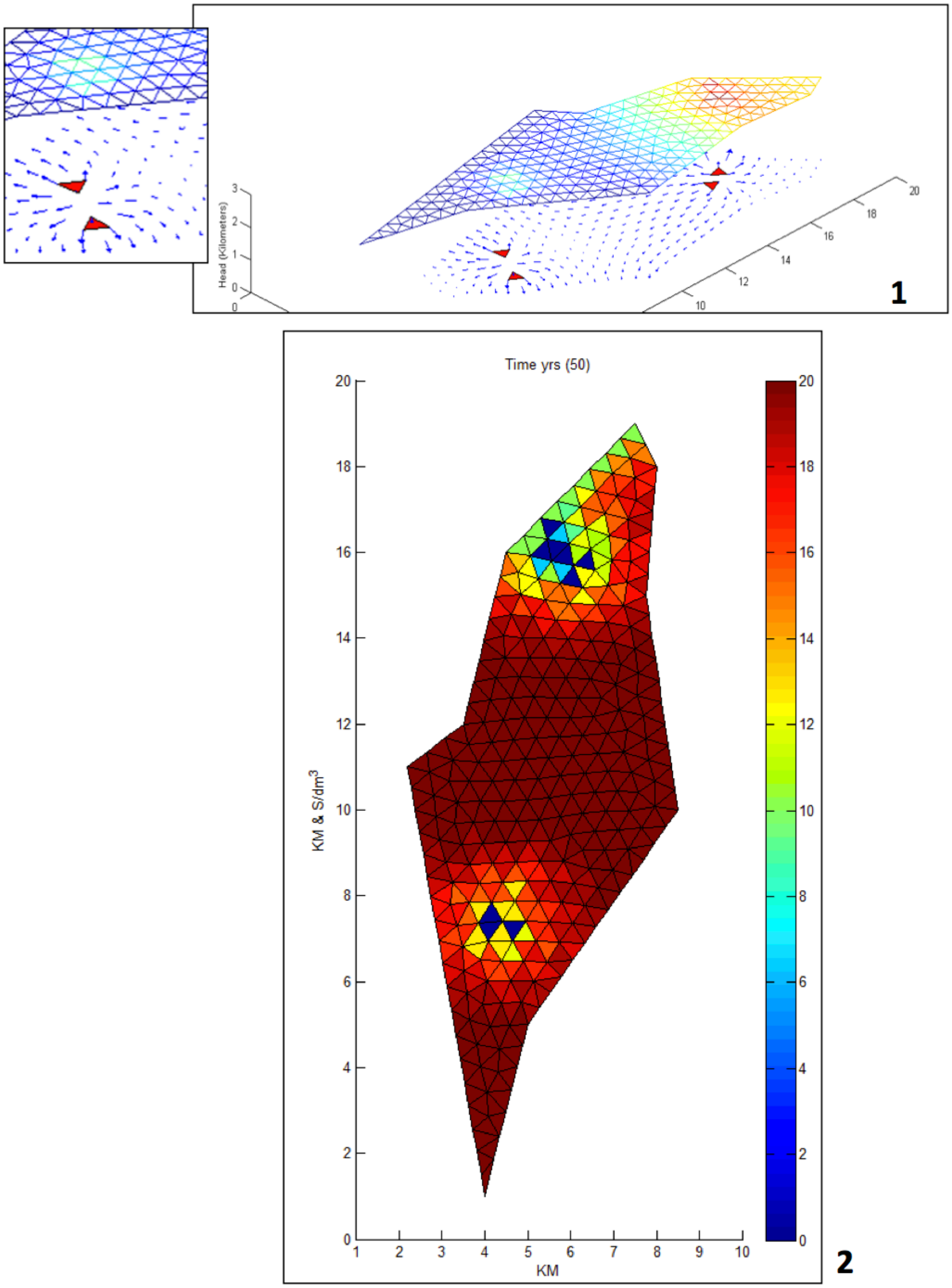

Figure 8. Groundwater recharge and transport models for assessing source of saline aquifer. (1) Groundwater flow vectors generated over a two dimensional finite element mesh with constant head boundary conditions and randomly generated direct recharge sites (red triangles). (2) Solution of numerically solved advection-diffusion equation (simulated for 50 years) over mesh with homogenous initial conditions and potential recharge at two locations.

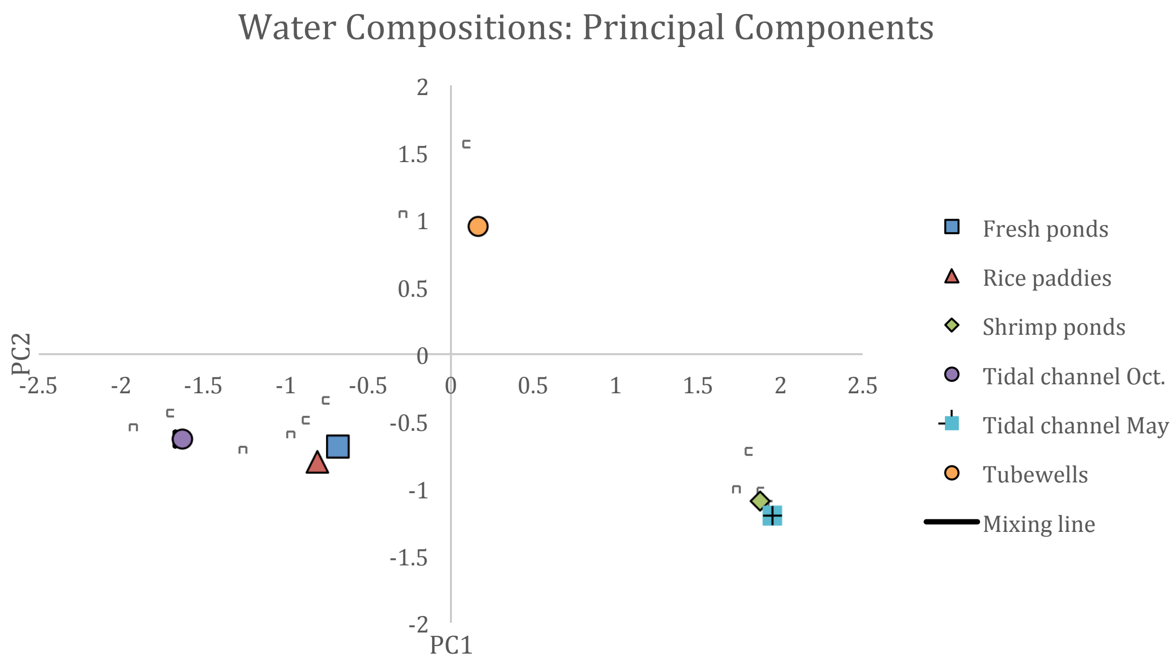

Figure 9. Plot of principal components for composition of local water sources. Principal components analysis was used with varimax rotation to obtain two principal components that account for 90% of the variance in the water compositions. Data from samples collected 2012 May (dry season) and October (wet season), including 113 water samples and 10 variables (log10 values of Al, As, Ba, Ca, K, Mg, Na, S, Sr, and Cl). The highest loadings on PC1 include Ca, K, Mg, Na, Sr and Cl and are all positively correlated. PC1 thus represents dissolution of soluble salts. As and S have the highest loadings on PC2, and are negatively correlated, suggesting that reduction of oxyhydroxides liberates As but causes sulfide precipitation. Overall, fresh (Oct) and saline (May) water from tidal channels comprise the seasonal end-members, with household ponds and rice paddies skewed toward the fresh-end member. The chemistry of shrimp-pond water is coincident with that of the saline tidal channels. The tubewell water is not potable and averages at 50:50 mixture of the fresh and saline end-members, with a strong diagenetic groundwater signature distinguishing its chemistry along the PC2 loadings.

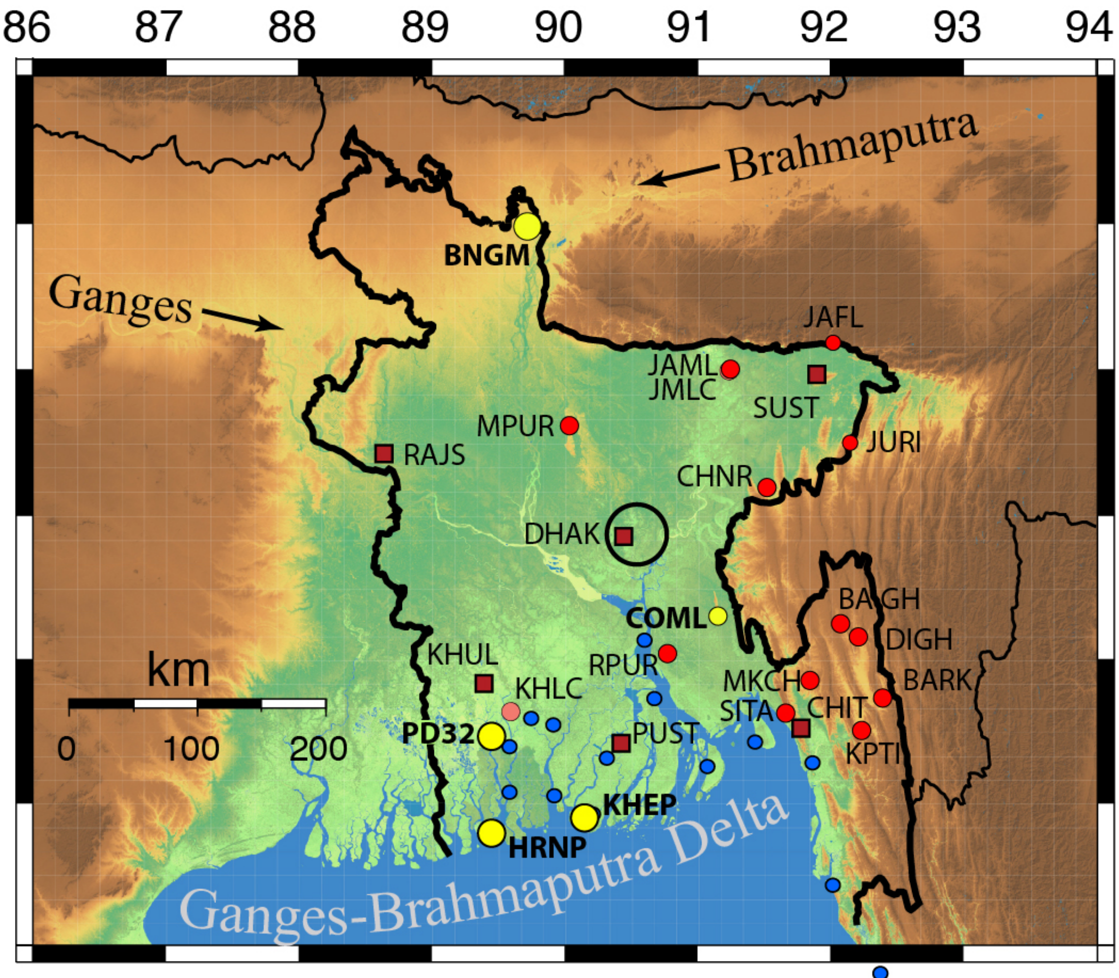

Figure 10. Distribution of GPS stations in Bangladesh. The red symbols are existing stations (triangles-2003, circles-2007and 2011). The sites installed in 2012 are in yellow. The four lager symbols have cellular communications for downloading the data. The two at the coast are be collocated with tide gauge stations. The large circle around Dhaka indicates the coverage for a network of 10 monuments being installed around the city. One is installed and the others will be installed in October 2013. One receiver will rotate among the monuments. Another receiver currently used for Fast Static surveys will assist in monitoring the Dhaka monuments when not in use. The blue circles are the locations of tide gauges whose records are being obtained from BIWTA (Bangladesh Inland Water Transport Authority).

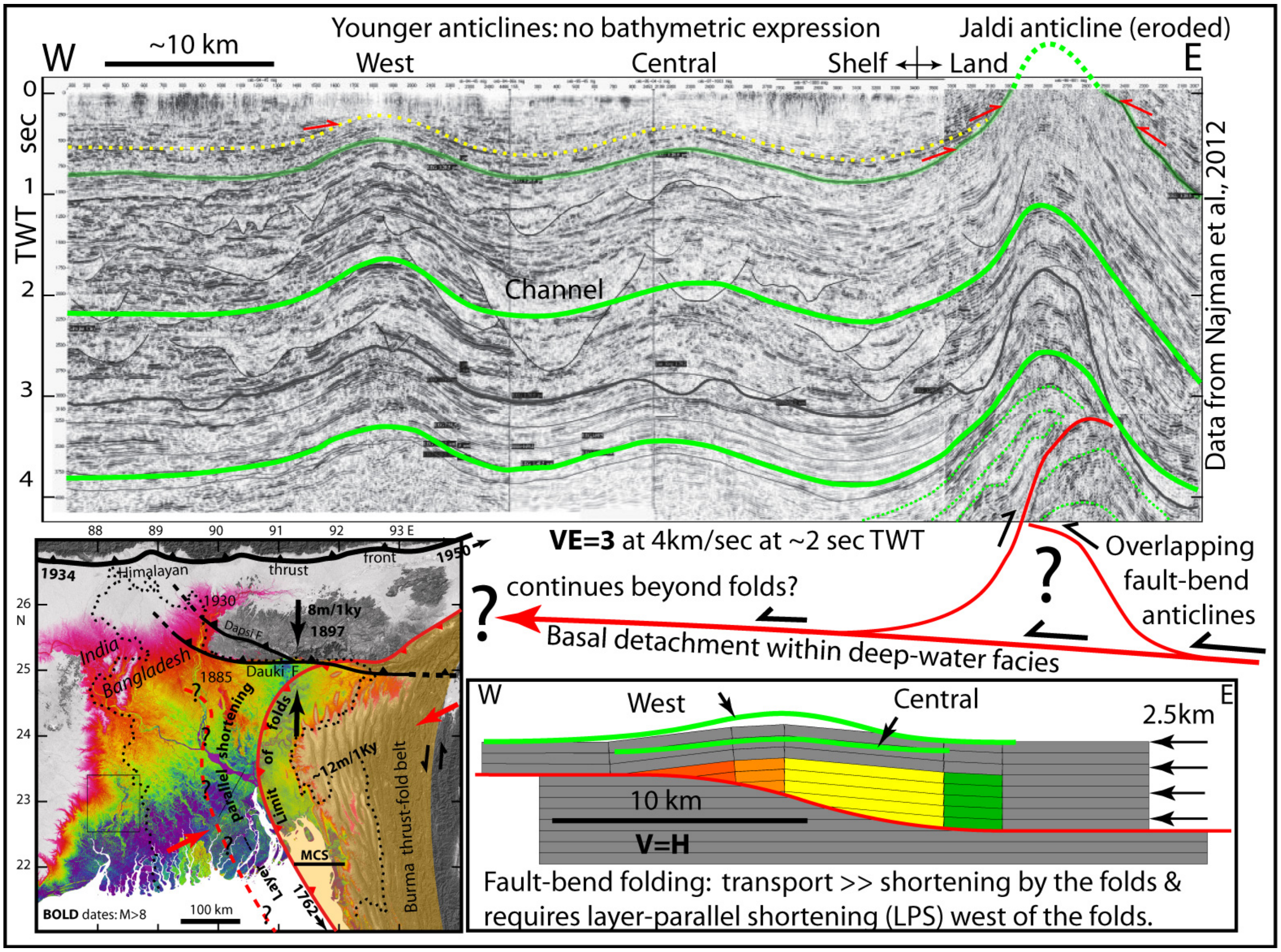

Figure 11. Two active contraction boundaries encroach into the Ganges-Brahmaputra delta: the deeply rooted Dauki thrust fault from the north and the Burma accretionary wedge from the east (inset map). Outer anticlines of the accretion fold belt are growing below the eastern coastal area of the delta ("MCS" in inset map locates profile). Onlaps (red arrows) show onset of folding that youngs to the west, confirming a forward (westward) progression of the deformation front into the coastal belt and major river pathways. Fault-bend models can easily reproduce the wide, low-amplitude and symmetrical anticlines, but require kilometers of layer-parallel shortening ahead of the folding that may strongly influence subsidence rates in the delta. Major damaging earthquakes are also marked by dates in inset map.

Table 1. Summary of project components contributing to the overarching research objectives of the study (see text).

Group	Subgroup	Topic	Lead (role)	Others
Social	Experimental	experimental methods to assess social cohesion, individual decision making, and factors that facilitate or inhibit collective action	B. Ackerly (PI)	C. Mo (assoc. PI), A. Carella (PhD)
	BEMS	enthnosurvey to assess patterns and processes of internal and international migration and role of environment stressors	K. Donato (PI)	A. Carrico (PDF), B. Piya (PhD)
	QCA	multi-community qualitative analysis of factors contributing to (in)stability at community to household levels, incl. physical and social data	B. Ackerly (PI)	
Physical	Landscape	landscape dynamics and evolution with coupling of tides, sea level, and sedimentation in human-altered and pristine settings	S. Goodbred (PI)	C. Wilson (PDF), L. Auerbach (MS)
	Geophysics	Absolute and relative land-surface motion; sea-level rise, subsidence and compaction	M. Steckler (PI)	
	Tectonics	earthquake threat and role of tectonic deformation on landsurface dynamics	L. Seeber (PI)	
	Hydrogeology	modeling of groundwater transport and hydrostratigraphic controls on advection and mechanical dispersion of saline waters	G. Hornberger (PI)	S. Worland (MS), C. Tasich (MS)
	Soil and Water	geochemistry of surface and ground waters in coastal plain and source of salinity in drinking water and impact on soils	J. Ayers (PI)	D. Fry (MS), G. George (MS)
Integration	ABM	computational agent-based modeling of resilience and stability; explore implications of plausible local scenarios for regional stability	J. Gilligan (PI)	J. Nay (PhD)
	Water Security	integrated assessment of factors affecting water security incorporating biophysical and socioeconomic parameters	L. Benneyworth (PhD)	J. Gilligan (PI)
	Visualization	GIS-based project framework and evaluating the capabilities and effectiveness of field data collection using handheld mobile devices	J. Camp (PDF)	M. Abkowitz (PI), L.Langsdon (staff), J. Abkowitz (staff)
	SALC	spatio-temporal analysis of land cover through remote sensing, including temporal cycles of agriculture, aquaculture, and flooding	C. Small (PI)	